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Estimation of Downwind Viable Airborne Microbes from a Wet Cooling Tower—Including Settling

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Abstract. In recent years, reuse of municipal waste water as the coolant in drift-producing cooling towers at electrical generating plants has become increasingly common. A hueristic model is presented that can be used to estimate the concentrations of viable airborne microbes in the drift from a wet cooling tower given the concentration of microbes in the cooling tower. The purpose of this presentation is to allow the nonmeteorologist to understand the factors affecting airborne concentration and to make crude estimates of ground-level concentrations of airborne microorganisms. Concentrations are calculated using a standard meterological method, the Gaussian dispersion model, in which terms have been included for droplet settling and microbial death rate.

Introduction

Anthropogenic introduction of airborne microorganisms into the atmosphere from large-scale sources is, or could become, a significant local contribution to downwind aerial contamination by these organisms. Elevated atmospheric concentrations of microorganisms have been observed near such sources as rendering plants [e.g. (25)], sewage treatment plants [e.g., (1,13)], and integrated urban activities [e.g., (7, 9, 16)]. Moreover, most agricultural practices, such as discing, harrowing, combining, and liquid manure spreading, and industrial sources, such as cooling tower drift from fossil and nuclear fueled power plants, have atmospheric inputs of unknown microbial composition and concentration.

The growing magnitude of some of these sources could pose potentially significant problems for the future. In the United States, treated sewage has been used as cooling-tower makeup water since 1951 and the practice is increasing. By 1973 three more utilities were using it, two had firm plans to use it, and five others were interested (11,21). A potential problem with these devices lies in the breakdown of fail-safe procedures when drift from a tower may carry quantities of microorganisms into the atmosphere at levels of 10^3 to 10^6 microbes/ml of water. For a more comprehensive review of large-scale atmospheric loading sources of airborne microbes see (16).

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The death rate of microorganisms injected into the atmosphere is a function of many biological and environmental variables [see (16)] and is an important consideration when estimating the concentration of any airborne microbial population. Death rates in the natural atmosphere have not been measured because of the great difficulties of quantitative observation. Laboratory measurements of microbial death rates in steady-state and, to a very limited extent, in dynamic environmental conditions (12) have been made using several cultured organisms [see (5)].

Many models have been used to estimate concentrations of particles downwind from point sources. These are summarized by Pasquill (19). Downwind concentrations of fungi, excluding loss by death considerations, have been estimated in experimental conditions [see (9)]. An estimator which includes a death factor was developed by Lighthart and Frisch (14,15) and by Biswas et al. (2). Some models which take into account drift deposition from cooling towers are discussed in *Cooling Tower Environment—1974* (4). These models generally require some meteorological expertise and a relatively large amount of input data.

The purpose of this paper is primarily heuristic and is intended to help the nonmeteorologist to understand the factors affecting the downwind concentration of microorganisms from a source such as a cooling tower.

The paper contains an atmospheric diffusion model for airborne microorganisms emitted in the drift from cooling towers that includes terms for both biological death and droplet deposition.

Model

Mathematical Development

The model used here to estimate the concentration of microbes from an elevated point source is known as the Gaussian plume model. This model can be derived assuming that the mean concentrations of gases or aerosols (such as microbes contained in water droplets) are normally distributed about the plume axis. (The normal distribution function is given by:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-x^2}{2\sigma^2}\right) \qquad \bar{x} = 0.$$

The model has been modified to account for the finite settling velocities of droplets in the plume, and an additional factor has been included to account for the death of microbes within the plume. The model below is actually the result of the superposition of many Gaussian plumes, one for each droplet-size category. The model is quasi-empirical: it is the theoretical solution to the diffusion equation for flow situations in which there is a constant wind and diffusivity. This may be nearly true in regions away from any boundaries, but for flow in the atmospheric boundary layer, where the wind and diffusivity are variable, the model gives an estimate of the concentration which may or may not be in accord

with the true concentration, depending on conditions. Estimates of 1-hour average concentrations are usually within a factor of 2 of values which would be observed under the given conditions: however, precise knowledge of all values of the variables affecting the plume may be practically impossible to obtain; thus it is more realistic to expect agreement with observations only to within an order of magnitude. The complexity of the terrain has nonquantifiable but significant effects on the concentrations. Empirically, in most cases the predictions of the Gaussian plume model fit the available observations at least as well as other models (19). Practically, the Gaussian plume model has the advantage of simplicity: no lengthy numerical integrations are necessary to obtain estimates of concentrations.

The form of the Gaussian plume model discussed here is:

$$\chi = \frac{bQ}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \sum_i q_i \exp \frac{-\left(H - V_{s_i}\frac{x}{u}\right)^2}{2\sigma_z^2} \exp\left(-\lambda \frac{x}{u}\right)$$

where χ is the mean number of microbes per unit volume of air (m^{-3}) at ground level and is a function of downwind and lateral distance from the source;

b is the number of microbes per unit volume of effluent (m^{-3}) at the source;

Q is the volume emission rate of effluent ($m^3 sec^{-1}$);

u is the mean wind speed (generally a 1-hour average) ($msec^{-1}$) and must be greater than zero for this model to be valid;

σ_y is the standard deviation of the horizontal plume spread (m), and is a function of downwind distance and atmospheric stability;

σ_z is the standard deviation of the vertical plume spread (m), and is a function of downwind distance and atmospheric stability;

y is the lateral distance from the mean position of plume axis (m);

q_i is the mass weighted proportion of particles in the ith size category (dimensionless);

H is the height above ground of the plume axis after the initial plume rise (m);

V_{s_i} is the settling speed of average microbe-containing droplet in the ith size category ($msec^{-1}$);

x is the downwind distance from the source along a line parallel to the mean plume axis (m); and

γ is the death rate of the microbes (sec^{-1}).

Term A represents the concentration on the mean plume axis at a given distance, x, from the source with no microbe death.

Term B accounts for lateral dispersion.

Term C accounts for vertical dispersion and differential droplet settling rates. It also modifies the formula so that the computed concentration is the ground-level concentration.

Term D takes into account the loss of microbes by death.

Determination of the Meterological Factors

The Gaussian plume model is valid for estimating mean concentrations only when meteorological and source conditions are stable for periods longer than about the distance of the receptor from the source divided by the mean wind speed. The σ_y and σ_z values that we use are based on 1-hour averages. Therefore, the wind speed, u, to enter into the equation is a mean wind, averaged over the appropriate period. If real wind is used in the equation, the wind speed used in the model must be representative of the wind at the plume centerline, not the local surface wind.

The expressions for the plume-spread factors, σ_y and σ_z, suggested here were determined empirically (23) based on an analysis of the available data on plume spread. These expressions are not appropriate for all situations and should not be taken as universally valid. The variation in plume-spread rates is determined primarily by the turbulence of the air in the vicinity of the plume. The level of the turbulence depends on the atmospheric stability, whether the air is being heated or cooled by the ground, the strength of the wind, and the roughness of the terrain. The effect of rough terrain, although quite difficult to assess quantitatively, tends to cause increased turbulence and thus a faster spreading of the plume. The vertical spread of the plume varies much more with the level of turbulence than the lateral spread. The expressions for the plume-spread factors are divided into four categories: 1 through 4, where 1 is for the most turbulent conditions and 4 is for the least turbulent case. The categories and expressions are presented in Table 1.

The maximum height, H, of the axis of the plume after leaving the stack is determined mainly by the characteristics of the stack, the temperature of the effluent gases, the wind speed, and the vertical temperature structure of the atmosphere. Since all these variables are not usually known, the problem of estimating plume height will not be dealt with here. For a discussion of plume rise the reader is referred to Briggs (3).

The minimum value of H is obviously the stack height itself. This is associated with the maximum ground-level concentration. As H increases, the ground-level concentration decreases nearly proportionally to $1/H^2$ (19).

Estimations made using this model are not valid for distances less than 100m or more than 10 km from the source because the plume-spread factors are not well determined outside that range. The model is also invalid for calms and very light wind situations.

Determination of Source Factors

The drift emission rate, Q ($m^3 sec^{-1}$), of water drops from a cooling tower is difficult to determine except by direct measurement. At most the drift emission is about 0.01% of the total circulating water flow or about 6% of the evaporation in the tower. For fossil-fuel or high-temperature gas-cooled reactor power plants the drift emission is about 0.03 l/sec/megawatt; for light-water reactor power plants the drift emission is about 0.04 l/sec/megawatt (8, 22).

Table 1. Plume spread factors for various atmospheric conditions

Category	Plume Spread Factors	State of Atmosphere	Possible Causes, Symptoms, and Effects
1	$\sigma_y = 0.40 \times x^{0.91}$, $\sigma_z = 0.40 \times x^{0.91}$	Highly turbulent; extremely unstable	Strong solar heating or cold air moving over warm ground often, but not necessarily, resulting in cumulus clouds and occasionally thunderstorms
2	$\sigma_y = 0.36 \times x^{0.86}$, $\sigma_z = 0.33 \times x^{0.86}$	Moderately turbulent	Ordinary sunny day in summertime (middle latitudes)
3	$\sigma_y = 0.32 \times x^{0.78}$, $\sigma_z = 0.22 \times x^{0.78}$	Wind caused turbulence	Windy, overcast if during the day
4	$\sigma_y = 0.31 \times x^{0.71}$, $\sigma_z = 0.06 \times x^{0.71}$	Stable; turbulence suppressed	Nighttime and light winds, or daytime in winter (middle latitudes) with low-level temperature inversion

The distribution pattern of the mass-weighted droplet sizes downwind of a cooling tower is not well known, but an inspection of the available data suggests that a log-normal distribution gives as good a fit as any of the simple theoretical distributions (20). For a large mechanical draft cooling tower at Oak Ridge, Tennessee, circulation rate 800 l/sec, the distribution of the data (6) was found to be adequately modeled by a log-normal distribution, with a geometric mean of 230 μm and a geometric standard deviation of 1.59. More modern towers may have much smaller drift rates and median drift-drop diameters (10). This distribution with these parameters is the one used in the following examples. The size distribution for natural draft towers would have a higher percentage in the smaller size ranges.

The settling rate for water drops can be approximated by

$$V_s = 0.025\, d^{1.47} \quad \frac{\text{cm}}{\text{sec}}$$

where d is the drop diameter in micrometers. This formula is based on data presented by Mason (17). The maximum error in the approximation is less than 20% for drop sizes ranging from 50 to 500 μm.

Determination of Biological Factors

The biological death rate, λ, as presented here can only be a crude guess at the rate occurring in the natural atmosphere. Our death rate value is derived from laboratory-grown pure cultures suspended in fluids of known composition and for the most part related to a static atmospheris environment [e.g., (5,16)]. To obtain more "realistic" death rate measurements, one must perform laboratory research with numerous microbial types, suspending and recovering fluids, and dynamic environmental conditions.

Discussion of Model Characteristics

Dependence of Concentration Estimates upon Droplet Size

The location of the peak microbial concentration is closest to the source and its magnitude is higher the larger the typical droplet size (Fig. 1). In this example, the variation in peak concentration is about a factor of two over a range in the median droplet size of a factor of three. In most situations the droplets are evaporating in their journey from the source to the ground so that the typical droplet size decreases with distance from the source. This is in addition to the decrease in mean size due to the early fallout of the larger droplets. Mason (17) estimates that droplets of less than 100 μm diameter usually evaporate before reaching the ground. The dotted line in Fig. 1 represents the case where fallout is neglected (i.e., $V_s = 0$). The real contribution of fallout to the concentration lies somewhere between the fallout computed for nonevaporating droplets (solid curves) and the concentration which would occur if there were no fallout.

Dependence of Concentration Estimates upon Plume Height

The downwind bacterial concentration is highly dependent on the plume height (Fig. 2); it decreases rapidly as the plume height is increased. There is no easy way to determine the plume rise in a particular situation without knowing the details of the meterological situation, although some theoretical and empirical formulas have been developed (3) and some models are presented in *Cooling Tower Environment—1974* (4). Unfortunately, in practice, measurements of the necessary variables are usually not available. For instance, under calm winds hot plumes from cooling towers tend to rise to many times the height of the stack, whereas under strong winds the plume may not rise much above the top of the tower. In general, the plume rise is less the more stable the atmosphere, other factors being equal. The maximum concentration estimate will result if one assumes the plume height to be the tower height. However, far downwind, lower plumes may yield lower concentrations than higher plumes due to earlier loss by settling from the lower plumes.

Dependence of Concentration Estimates upon Wind Speed

The ground-level microbial concentration decreases with increasing wind speed, an order of magnitude increase in wind speed yielding an order of magnitude decrease in concentration if the variation in-with wind speed is neglected (Fig. 3). Since plume rise generally decreases with increasing wind speed, this effect is in reality much less than an order of magnitude. Although in the equation terms C and D increase with increasing wind speed, term A dominates for values of the parameters valid for the atmosphere. When fallout is considered (solid curves), the lower the wind speed the closer the peak concentration to the source, but if fallout is neglected the downwind distance of the peak concentration is independent of wind speed.

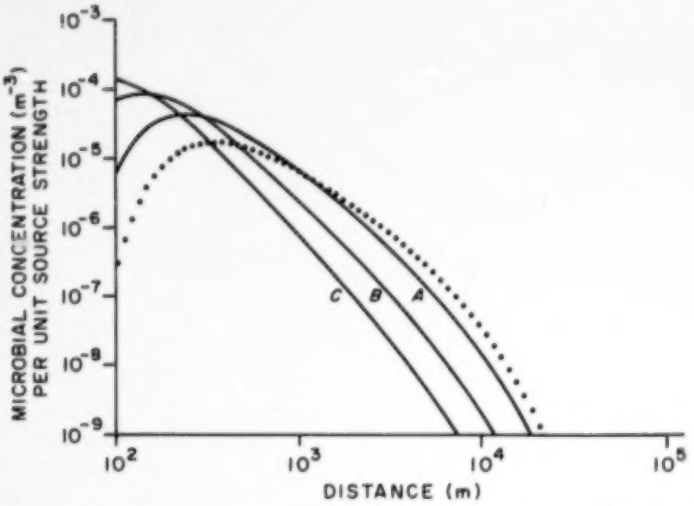

Fig. 1. Variation of concentration with droplet size. A, geometric mean 100 μm; B, geometric mean 200 μm; C, geometric mean 300 μm. The values of the parameters used in the computations for all the figures are: wind speed, 5m/sec; plume height, 30 m; bacterial death rate, 0.001/sec; stability category, 3; geometric mean, 230 μ; and geometric standard deviation, 1.59; except as noted. A log-normal mass-weighted droplet-size distribution is assumed. The dotted lines denote the results of the calculations if the settling of the droplets is neglected.

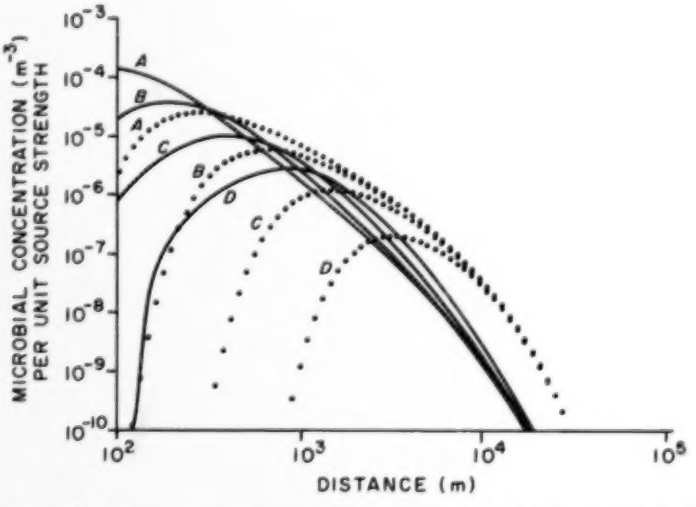

Fig. 2. Variation of concentration with plume height. A, plume height 25 m; B, plume height 50 m; C, plume height 100 m; D, plume height 200 m.

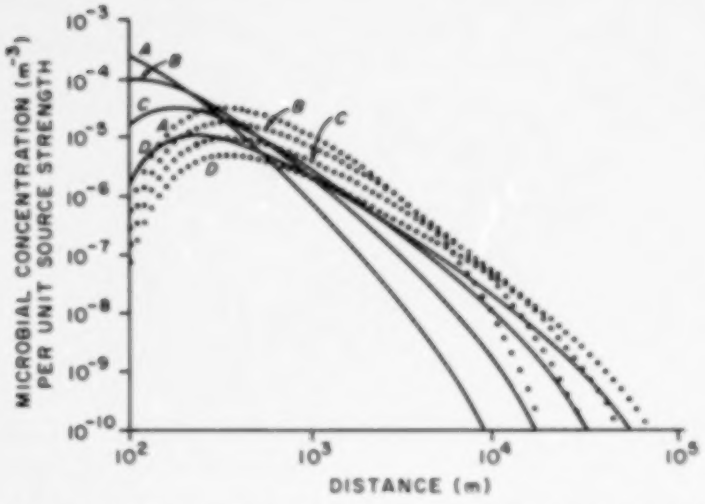

Fig. 3. Variation of concentration with wind speed. A, wind speed 2.5 m/sec; B, wind speed 5 m/sec; C, wind speed 10 m/sec; D, wind speed 20 m/sec.

Dependence of Concentration Estimates upon Microbial Death Rate

As would be expected, the near-source concentration of microorganisms is nearly independent of death rate, whereas the more distant concentrations are highly dependent on death rate. Figure 4 shows this dependence for the curve where fallout is considered (solid curves) and where it is neglected (dotted curves).

Dependence of Concentration Estimates upon Stability

For droplets having a median size of about 200 μm, the estimated concentration downwind varies much less with atmospheric stability or turbulence level than would be expected if fallout were neglected (Fig. 5). For droplets this large, the effect of the gravitational settling is greater than the effect of turbulent diffusion. For evaporating droplets this effect would be less apparent and the estimated concentrations would approach model predictions which do not include fallout considerations.

Deposition Estimates

The deposition rate (number of microbes per square meter per second) can be estimated by a slight modification of the concentration model. If each settling velocity, V_s, is multiplied by its corresponding proportion, q_i, within the size

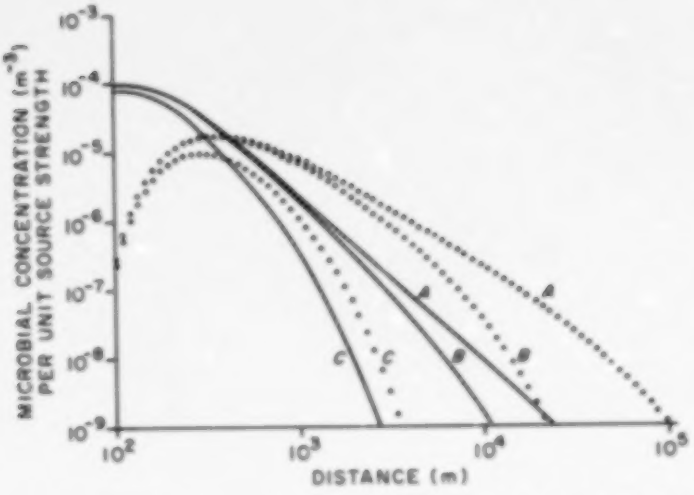

Fig. 4. Variation of concentration with death rate. A, microbial death rate 0.0001/sec; B, microbial death rate 0.001/sec; C, microbial death rate 0.01/sec.

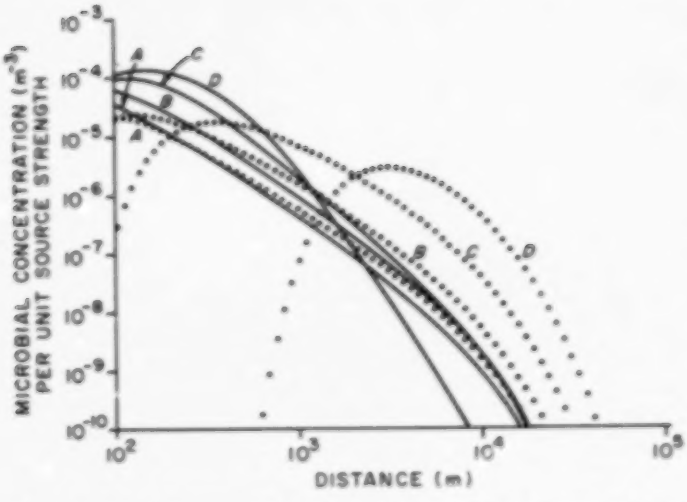

Fig. 5. Variation of concentration with stability. A, stability category 1; B, stability category 2; C, stability category 3; D, stability category 4.

class and then substituted for q, in the equation, the model then yields deposition rates. Figures 6 and 7 show the variation of deposition rates with wind speed and effective plume height, the factors causing the most variation.

Sample Calculation

It has been estimated that treated sewage water can contain about 10^9 bacteria per cubic meter (18). Also, the biochemical oxygen demand and chemical oxygen demand used in coolant water at Lubbock, Texas, were found to be 10 mg/l and 40 mg/l, respectively (E. F. Jones, personal communication). This corresponds to a bacterial concentration of about $10^{12}/m^3$ (13). Using the lower estimate and the estimated drift emission rates from the mechanical draft cooling towers at Denton (E. E. Jones, personal communication) and Lubbock, Texas, which are 0.062 m^3/sec and 0.18 m^3/sec, respectively, in conjunction with the model, one can estimate the downwind concentrations and deposition rates. If one assumes a mean wind speed of 5 m/sec, a plume height of 30 m, a bacterial death rate of 0.001/sec, an atmospheric stability category of 3, and a log-normal droplet size distribution with geometric mean and standard deviation of 230 μm and 1.59, respectively, one can calculate (or use Figs. 5 and 6) that the mean bacterial concentration due to cooling tower drift at 1 km directly downwind would be about 100 bacteria per cubic meter at Denton and 400 bacteria per cubic meter at Lubbock. The corresponding deposition rates are 40 and 100 bacteria per square meter per second, respectively. This represents the inhalation at Denton and Lubbock of approximately 40 and 140 viable bacteria per hour 1 km downwind from the source assuming a human tidal volume of 0.5 l and a breathing rate 720 cycles/hour (24). This says nothing about the allergenic potential of nonviable microbes in the plume.

Conclusions

The mathematical approximation presented in this paper is a practical general model for estimating concentrations of viable microorganisms in the atmosphere downwind from a point source. With the aid of the figures, given the amount of microorganisms in the effluent, one can compute the approximate concentrations and deposition rates downwind from a mechanical draft cooling tower for some meterological situations. The effect of varying each of the input parameters can be seen for fixed values of the others. The model equation can be solved using a computer and a relatively simple program for any desired values of the input parameters. The model is not a substitute for a thorough meterological analysis of a particular situation at a particular cooling tower site; it only crudely approximates the results of the diffusion process in the atmosphere. Nevertheless, the difficulty in making accurate estimates lies not so much with inadequacies inherent in the model, at least when considering steady mean winds over homogeneous ground, but with the inadequacies of the estimates of the input "parameters." The state of the atmosphere is highly variable and only partially predictable; therefore, the so-called meteorological parameters are only partially

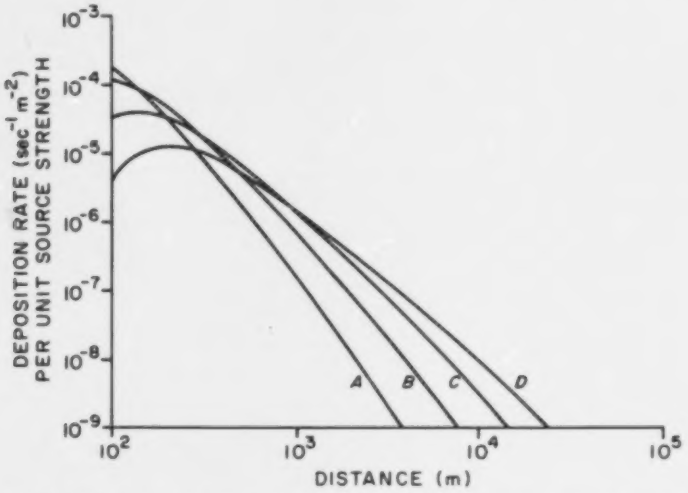

Fig. 6. Variation of deposition rate with wind speed. A, wind speed 2.5 m/sec; B, wind speed 5 m/sec; C, wind speed 10 m/sec; D, wind speed 20 m/sec.

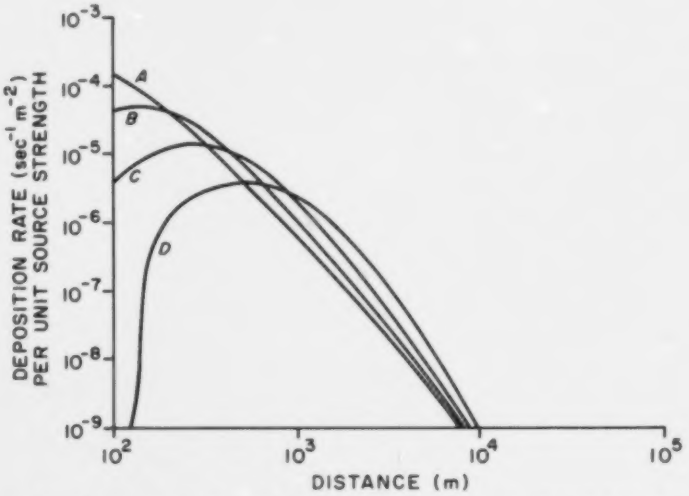

Fig. 7. Variation of deposition rate with plume height. A, plume height 25 m; B, plume height 50 m; C, plume height 100 m; D, plume height 200 m.

predictable. The bacteriological factors are also difficult to assess. For instance, the death rate of bacteria contained in evaporating water droplets falling and diffusing in the atmosphere cannot be practically measured, and one must rely on laboratory experiments, whose comparability with the "real" world is unknown.

Despite the limitations on the validity of the microbial concentrations estimated by this model, if one carefully assesses the specific situation, the predictions can yield insight into problems that could occur downwind from a source of pathogenic bacteria.

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